

Retrospective Dose Assessment for the Population Living in Areas of Local Fallout from the Semipalatinsk Nuclear Test Site Part I: External Exposure

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A short analysis of all 111 atmospheric events conducted at the Semipalatinsk Test Site (STS) in 1949–1962 with regard to significant off-site exposure (more than 5 mSv of the effective dose during the first year after the explosion) has been made. The analytical method used to assess external exposure to the residents living in settlements near the STS is described. This method makes use of the archival data on the radiological conditions, including the measurements of exposure rate. Special attention was given to the residents of Dolon and Kanonerka villages exposed mainly as a result of the first test, detonated on August 29, 1949. For the residents of those settlements born in 1935, the dose estimates calculated according to the analytical method, are compared to those derived from the thermoluminescence measurements in bricks and electron paramagnetic resonance measurements in teeth. The methods described in this paper were used for external dose assessment for the cohort members at an initial stage of an ongoing epidemiological study conducted by the U.S. National Cancer Institute in the Republic of Kazakhstan. Recently revised methods and estimates of external exposure for that cohort are given in another paper (Simon et al.) in this conference.

INTRODUCTION

At present the scientists of the U.S. National Cancer Institute are conducting an epidemiological study aimed at: (1) evaluating thyroid disease prevalence among the population exposed to fallout from the Semipalatinsk Test Site (STS) and (2) estimating the risk of radiation dose-related thyroid disease, including cancer, in a population with protracted exposure to mixed gamma and beta radiation from fallout.¹⁾

An important part of this study is assessment of individual thyroid doses from external and internal irradiation for a selected cohort of about 3,000 people that live in six heavily

exposed (Dolon, Kanonerka, Korostevskii, Kaynar, Sarzhal, and Kara-Aul) and two lightly exposed villages (Bolshaya Vladimirovka and Novopokrovka) near the STS.¹⁾ Thyroid dose assessment is carried out on the basis of the methodology developed by joint efforts of the scientists of the Institute of Biophysics and some other Institutes of the Ministry of Public Health of the USSR, biologists and physicists of the STS, as well as of the specialists from other organizations involved in radiation protection problems.²⁾ The main features of this methodology were discussed by the scientists in the Russian Federation (RF) and the U.S. and this methodology was adopted by the Ministry of Public Health of the RF as an official document. The most important input parameter in the methodology is exposure rate at the height of 1 meter above ground surface measured or interpolated for a settlement after each event resulted in local fallout outside the territory of the STS. Efforts are under way to assess validity of the dose estimates and improve them where possible. On-going activities include a detailed comparison of the environmental transfer models used in Russia and in the U.S., as well as the estimation of external doses from thermoluminescence (TL) measurements in bricks obtained from local buildings and electron paramagnetic resonance (EPR) measurements in teeth taken from local residents. Special attention was paid to the residents of Dolon

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village that has been identified as the most highly exposed location in the vicinity of the STS. Recently available TL^{3,4)} and EPR^{5,6)} measurements for Dolon village show the estimates of external dose to the residents substantially less than those derived from historical measurements of exposure rate (0.5 Gy or less compared to 1 Gy or more). With respect to village Kanonerka this difference is less but also is seen in favor of the estimates derived from historical measurements. In order to clarify the possible reasons for that difference, we provide a short description of the methodology of reconstructing external doses to residents of settlements near the STS. As well the estimates of exposure rates obtained by using different methods are discussed.

MATERIALS AND METHODS

Chronology of nuclear weapons testing conducted at the Semipalatinsk test site

The first nuclear test in the USSR was conducted at the Semipalatinsk Polygon on August 29, 1949. During the following 40 years, 456 nuclear explosions were carried out, including 111 atmospheric events (86 events in air and 25 surface events) between 1949 and 1963.⁷⁾ After the onset of the Limited Test Ban Treaty signed in 1963, the tests at the STS were restricted to underground shafts and tunnels so that, with a few exceptions, little or no off-site environmental contamination was caused. The event numbers given here are according to the official classification of the nuclear events conducted in the USSR.⁷⁾ The last event conducted at the STS was on October 19, 1989.

The atmospheric events provided the main contribution to

the radioactive contamination of the environment and to the radiation exposure of the population. The total yield of these events is reported to be 6.58 Mt.⁸⁾ Of those 111 events, only for 55 events was the exposure rate from fallout measured off-site (outside the territory of the STS) in the Republic of Kazakhstan detected to be higher than the background exposure rate.^{7,8)}

Atmospheric significant events

During the testing period it was revealed that the radiological conditions in the areas of fallout depended upon not only the type and composition of fission material, yield of event and height of detonation above ground surface, but also upon meteorological and seasonal conditions, as well as upon landscape features under the moving radioactive cloud. The doses received were extremely variable and depended on location, lifestyle, and other factors. The most important were the four following events: #1 (August 29, 1949; yield of 22 kt), #2 (September 24, 1951; 38 kt), #4 (August 12, 1953; 400 kt), and # 28 (August 24, 1956; 27 kt). It is estimated that these events contributed more than 95% of the collective dose to the population living in areas close to the STS.

During the atmospheric testing era the maximum permissible dose to the population from external irradiation from a given event was that corresponding to an exposure outdoors of 0.5 R according to the Radiation Safety Standards that were valid at that time. It means that no special countermeasures for the populations were required if the exposure outdoors was expected to be less than 0.5 R. So, only those events that might have resulted in exposures of more than

Table 1. Characteristics of the 11 most significant events conducted at the STS.¹⁵⁾

Event number according to ⁷⁾	Date (dd.mm.yy)	Height above ground, m	Type	Total yield, kt
First group				
1	29.08.49	30	Tower	22
2	24.09.51	30	Tower	38
4	12.08.53	30	Tower	400
18	30.10.54	55	Tower	10
28	24.08.56	93	Tower	27
148	07.08.62	0	Surface	9.9
Second group				
13	05.10.54	0	Surface	4
19	29.07.55	2.5	Surface	1.3
20	02.08.55	2.5	Surface	12
26	16.03.56	0.4	Surface	14
41	22.08.57	1880	Balloon	520

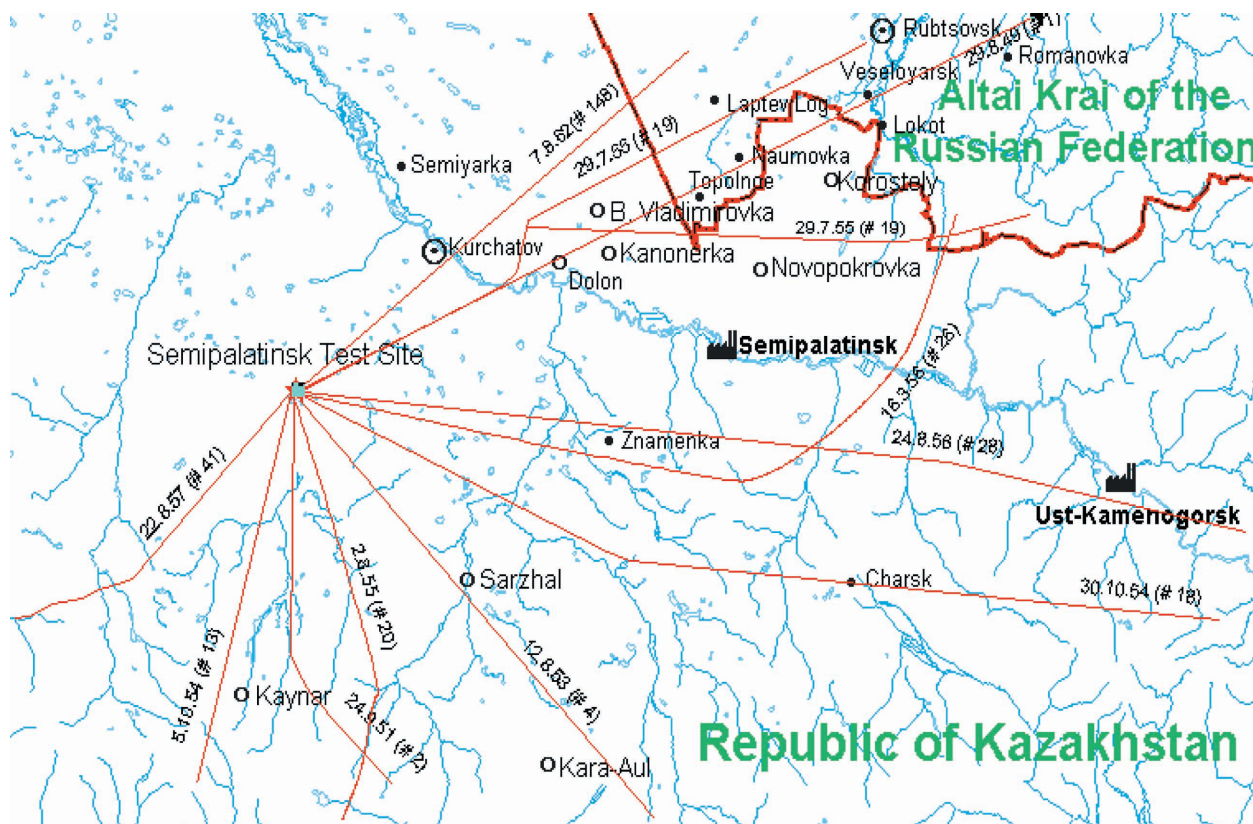


Fig. 1. Trajectories of the radioactive clouds related to the most significant events and location of the settlements of which residents are involved into the ongoing epidemiological study.

0.5 R in inhabited areas were considered to be significant.

After the end of nuclear weapons testing the problems related to possible consequences of radiation exposure at local and regional levels received increased attention. A new criterion to select significant nuclear events was developed based on current Radiation Safety Standards⁹⁾ and on the Concept of radiation medicine and social protection.¹⁰⁾ According to this criterion an event is considered to be significant if the effective dose to an adult living off-site at the point of maximum exposure rate during the year following the nuclear explosion would exceed 5 mSv.

On the basis of the archival materials related to the characteristics of the events and to meteorological and radiological conditions, a detailed analysis has been carried out of the radiation exposures to the populations following each atmospheric event. Of 55 events for which fallout off-site was detected, only 11 were found to satisfy this criterion. These 11 most significant events were classified into two groups (Table 1). The first group includes six events for which the lifetime effective dose to an adult living off-site at the point of maximum exposure rate would exceed 50 mSv. The second group includes five events for which the effective dose to an adult living off-site at the point of maximum exposure rate during the year following the nuclear explosion would exceed 5 mSv but the lifetime effective

dose would not exceed 50 mSv.

Selection from all nuclear events conducted at the STS of only the 11 most significant events allows the specialists to concentrate their efforts on the analysis of radiological conditions and dose assessment from those events that might have resulted in substantial exposure to the populations.

Trajectories of the radioactive clouds based on the data^{11–14)} related to the most significant events, as well as the locations of the eight settlements included into an ongoing epidemiological study and some other settlements where the members of the cohort lived during a prolonged period of time in 1949–1962 are shown in Fig. 1.

Methodology used to assess external whole-body dose to the residents

A detailed description of the methods used in the methodology of estimation of external exposure to the populations living in the areas of local fallout from nuclear tests is available in.²⁾ This methodology is based on the coupling of data on radiation exposure of the populations and environmental transfer models. The usable data are maintained in the archives of the Ministry of Defense and of the Ministry of Health, as well as those of other organizations of the Russian Federation that took part in nuclear testing operations at the STS. The most useful data are exposure rates mea-

sured along the trajectories of the radioactive clouds. The exposure-rate measurements, which were usually taken aboard low-flying aircraft, were sometimes supplemented with ground-level monitoring. In the archives of the Ministry of Defense of the Russian Federation, the measurement data of exposure rate are presented in different forms: (1) original measurements with indication of time, location, height above ground surface, and reading of the instrument, and (2) maps showing isopleths of exposure rates normalized to some definite post-detonation time.

The methodology of assessment of external whole-body dose consists of two steps. In the first step the radiological conditions in a settlement located in the area of local fallout are reconstructed and absorbed dose in air is assessed. In the second step the dose assessment for the population groups living at the location of interest is carried out taking into account their lifestyle and dietary habits.

The model used to predict or reconstruct the radiological conditions after each test in areas where measurements were lacking, requires information on test yield, type and composition of fission material, date and time of explosion, height of radioactive cloud top, height of detonation above ground surface, and average wind speed over the height of the radioactive cloud.²⁾

The main parameters characterizing the radiological conditions at the location of interest and used in the external exposure assessment are derived by means of the model:

- fallout arrival time, $H+t$ (h);
- duration of fallout Δt (h);
- exposure rate at time $H+24$ h, P_{24} (mR h⁻¹).

Whenever possible, the values of exposure rate, P_{24} , were derived from the available measurements of exposure rate in the location of interest or in its vicinity.¹¹⁻¹⁴⁾

Using the above data, it is possible to assess absorbed dose in air at the point to which the exposure rate is assigned.

A total absorbed dose in air, D_{air} , due to fallout consists of two components: (1) dose from radioactive cloud, D_{cloud} , during its passage through a given point from the fallout arrival time, t_0 , to the end-of-fallout time, $t_0+\Delta t$, and (2) dose from fallout, D_{fallout} , deposited on the ground from the end-of-fallout time, $t_0+\Delta t$, until infinity.

$$D_{\text{air}} = D_{\text{cloud}} + D_{\text{fallout}} \quad (1)$$

where D_{air} is a total absorbed dose in air, in units of mGy;

D_{cloud} is absorbed dose in air from gamma radiation emitted from the radioactive cloud, in units of mGy;

D_{fallout} is absorbed dose in air from gamma radiation emitted from the activity deposited on the ground, in units of mGy.

The empirical equation to estimate D_{cloud} has the following form:²⁾

$$D_{\text{cloud}} = k_{\text{air}} \times 0.5 \times \Delta t \times P_{\text{res}} \times (1 + 1.5 \times q^{-0.04}) \quad (2)$$

where $k_{\text{air}} = 8.7 \times 10^{-3}$ mGy mR⁻¹ is a conversion coefficient to absorbed dose in air, in units of mGy mR⁻¹;

Δt is duration of fallout, h;

P_{res} is exposure rate at the end-of-fallout time, in units of mR h⁻¹;

q is total yield of the explosion, in units of kt.

In order to assess dose from fallout, D_{fallout} , it is necessary to determine the functional form of the time-dependence of exposure rate. This dependence was taken from,¹⁶⁾ according to which the exposure rate $P(t)$ at any time t (starting from the end-of-fallout time, $t_0+\Delta t$) can be assessed on the basis of available historical measurement of exposure rate $P(t_m)$ performed at time t_m as follows:

$$P(t) = P(t_m) \times (t/t_m)^{-n} \quad (3)$$

where $n = 1.3$ for $t_0 + \Delta t < t \leq 100$ h;

$n = 0.9$ for $100 < t \leq 1000$ h;

$n = 1.2$ for $t > 1000$ h;

$t_0 + \Delta t$ is the end-of-fallout time, h.

Then, the dose from fallout, D_{fallout} , is estimated as

$$D_{\text{fallout}} = k_{\text{air}} \times \sum_{i=1}^3 \int_{t_{b,i}}^{t_{e,i}} P(t) dt \quad (4)$$

where $t_{b,1}$, $t_{b,2}$, $t_{b,3}$ are equal to $t_0+\Delta t$, 100 h, and 1000 h, respectively, h;

$t_{e,1}$, $t_{e,2}$, $t_{e,3}$ are equal to 100 h, 1000 h, and ∞ , respectively, h.

In order to assess external whole-body dose to the residents it is necessary to take into account their lifestyle and type of residence of the population groups living at the location of interest:

- age-dependent number of hours spent outdoors; and
- values of the shielding factor related to the ratio of the outdoor and indoor exposure rates for the gamma radiation emitted from the radioactive cloud and that for the activity deposited on the ground.

The equation to assess a whole-body dose, D_{body} , is as follows:

$$D_{\text{body}} = D_{\text{air}} \times CF \times [t_{\text{outdoors}} + (t_{\text{day}} - t_{\text{outdoors}})/k_{\text{shield}}]/t_{\text{day}} \quad (5)$$

where CF is a conversion factor to convert absorbed dose in air to absorbed dose in the body (μGy per μGy) depending upon age (assuming 100% outdoor occupancy), dimensionless;

t_{outdoors} is time spent outdoors, h;

$t_{\text{day}} = 24$ h, hours in a day; and

k_{shield} is the shielding factor related to the ratio of the outdoor and indoor exposure rates for gamma radiation emitted from the activity deposited on the ground, dimensionless.

Table 2 shows the values of parameters related to the radiological conditions, shielding factor, lifestyle for the residents born in 1935 (14 y in 1949) and the estimates according to the above methodology of average external whole-

Table 2. Characteristics of fallout and the estimates of average external whole-body dose for the residents born in 1935 accounting for their lifestyle and type of residence in two settlements Dolon and Kanonerka.¹⁵⁾

Settlement	Event		Time of arrival of fallout, H+t, h	Duration of fallout Δt , h	Exposure rate at H+24 h, P_{24} , mR h ⁻¹	Time spent outdoors per day, t_{outdoors} , h	Shielding factor, k_{shield}		External whole-body dose, mGy
	Date	Number					cloud	ground	
Dolon	29.08.49	1	2.4	2.0	1150	8	1	3	1240
	29.07.55	19	3.1	2.1	0.5	16	1	3	0.7
	7.08.62	148	10.5	7.6	1.0	16	1	3	1.1
Kanonerka	29.08.49	1	3.0	2.4	250	8	1	3	250
	29.07.55	19	4.2	2.8	0.6	16	1	3	0.8
	7.08.62	148	13.2	9.4	1.0	16	1	3	1.1

body dose to those residents from Dolon and Kanonerka villages exposed to the most significant events.¹⁵⁾ Historical measurements of exposure rate for Dolon and Kanonerka villages following each significant event were taken from.^{11–14)} As can be seen from Table 2 more than 99% of total external dose to the residents in both villages during the atmospheric nuclear testing era 1949–1962 was provided by event #1. Thus, the accumulated external dose for those residents can be assigned to event #1.

RESULTS AND DISCUSSION

The above method was applied to assess absorbed dose in air at the locations where historical measurements of exposure rate for Dolon and Kanonerka villages were performed. Data given in Table 2 were used as input data in the calculations of whole-body dose estimates for the residents born in 1935. Results of the calculations together with the estimates of external dose to the residents in both villages available in the literature are presented in Table 3.

As can be seen from Table 3 the dose estimates calculated using a single historical measurement of exposure rate in Dolon village are generally higher than the estimates based on TL and EPR measurements (1 Gy or more compared to 0.5 Gy or less). A preliminary estimate of absorbed dose in air near the site where a former church is located 1.4 Gy³⁾ at a later time was revised and a more accurate and reliable estimate is equal to 0.48 ± 0.11 Gy.⁴⁾ The latter estimate taking into account behavioral and environmental factors is in a reasonable agreement with the estimates of individual external doses to the residents derived from EPR measurements showing the dose range from 0 to 0.45 Gy.^{5,6)} Variation in the dose estimates based on historical measurements of exposure rates^{15,17–20)} are due to different exposure-rate-vs.-time profile used in calculations. Fitting of actual data by $t^{-1.2}$, t^{-n} , or a sum of 10 exponential functions allows the difference between calculated and actual exposure rates to be within 30%, 10% and 2%, respectively. Although the exact

location of a single historical measurement for Dolon is uncertain, the specialists involved in dose calculation^{11–14)} consider it to have been performed at the trace axis that is about 1.5 km northwest of Dolon village. It is important to stress that in dose calculations based on this historical measurement a uniform distribution of fallout (and exposure rate) across the village was assumed and it was taken to be equal to that on the trace axis. Such a conservative assumption was taken in order not to underestimate external dose to the residents. However, in reality it has led to significant overestimation of external dose to the residents of Dolon village. Because, as it was noted in,¹²⁾ the width of the fallout cloud passing over Dolon was very narrow. Thus, exposure rate profile versus off-axis distance should be taken into account to assess realistic doses to the Dolon residents. The problem is how to assess that profile. In principle, it can be derived from contemporary measurements of soil cesium content over Dolon and its vicinity. This approach was used in^{4,19–21)} to provide more realistic assessment of external exposure at Dolon. At the same time one should keep in mind that variation of cesium fallout is not identical to variation of exposure rate because of fractionation of radionuclides in fallout particles. According to²²⁾ large particles are depleted in ¹³⁷Cs and other volatile nuclides, while small particles are enriched in ¹³⁷Cs. Also, it is known that the fraction of large particles in fallout along the axis is substantially higher than that at off-axis distance,²²⁾ so the decrease of ¹³⁷Cs content in soil versus off-axis distance is expected to be steeper than that of the exposure rate because the main contribution to the exposure rate is provided by refractory radionuclides. It is possible to compare the decrease of exposure rate and of the ¹³⁷Cs deposition fallout between the point at the axis and the site of the former church in Dolon located about 3.2 km southeast of the axis. According to⁴⁾ the maximum value of the ¹³⁷Cs deposition density was found in 1989 by the specialists of the STS at 2 km to the northwest of Dolon and was equal to 8.9 kBq m⁻². The level of ¹³⁷Cs deposition density for soil around the former church

Table 3. Estimates of external dose for the residents of villages Dolon and Kanonerka assessed by different methods.

Reference	External dose	Method	Comments
Dolon			
17)	1.1 Sv ^a	Reconstruction using an archival map with isopleths of exposure rates. Used $t^{-1.2}$ decay rate model.	Average effective dose
18)	2.2 Sv	Reconstruction using single historical measurement. Used $t^{-1.2}$ decay rate model.	Average effective dose
15)	1.2 Sv	Reconstruction using single historical measurement. Used $t^{-1.2}$ decay rate model.	Average effective dose
19)	0.72 Gy	Reconstruction using single historical measurement. Used TRINITY test decay curve consisting of ten exponents.	Average whole-body dose
19)	0 to ≈ 0.75 Gy, median of 0.32 Gy	Contemporary measurements of ^{137}Cs in 18 soil samples taken at 9 sites	Average whole-body dose
20)	2.26 Gy	Reconstruction using single historical measurement. Used $t^{-1.2}$ decay rate model.	Absorbed dose in air at the trace axis
This paper	2.4 Gy	Reconstruction using single historical measurement. Used t^{-n} decay rate model.	Absorbed dose in air at the trace axis
3)	1.42 Gy	Thermoluminescence measurements (TL) in bricks	Absorbed dose in air at the site where the former church building is located
4)	0.475 ± 0.11 Gy	TL measurements in bricks	Absorbed dose in air at the site where the former church building is located
5)	0.176 Gy	Electron paramagnetic resonance (EPR) measurements in teeth	Individual dose for 1 person using 3 samples. Resided and exposed in 1949
6)	0 to 0.450 Gy, median of 0.139 Gy	EPR measurements in teeth	Individual doses for 11 persons. Resided and exposed in 1949
22)	median of 0.08 Gy	EPR measurements in teeth	Individual doses for 9 persons. Report from the NIST to the NCI, 2002
Kanonerka			
15)	0.25 Sv	Reconstruction using single historical measurement. Used $t^{-1.2}$ decay rate model.	Average effective dose
This paper	0.50 Gy	Reconstruction using single historical measurement. Used t^{-n} decay rate model.	Absorbed dose in air at the site where historical measurement was performed
4)	0.24 ± 0.06 Gy	Thermoluminescence measurements in bricks	Absorbed dose in air near the brick house

^a – Effective dose in Sv is numerically equal to whole-body dose in Gy.

is estimated to be 3.74 kBq m^{-2} adjusted to 1989.⁴⁾ Assuming global fallout in 1989 to be about 2 kBq m^{-2} , one can assess the scaling factor as about 0.25 ($((3.74-2)/(8.9-2) = 0.25)$). The scaling factor for exposure rate is derived from comparison of the estimate of absorbed dose in air assuming no shielding at the axis (2.4 Gy) and that near the former church (0.48 Gy). It is estimated to be about 0.20. According to these estimates the decrease of ^{137}Cs content in soil (factor of 0.25) is steeper than that of the exposure rate (factor of 0.20) as was expected from what was stated above.

With respect to Kanonerka village the absorbed dose in air

(0.50 Gy) calculated using a single historical measurement of exposure rate for Kanonerka is twice that (0.24 Gy) derived from the TL measurements. One can suppose that variation of exposure rate over Kanonerka was not so drastic as it was over Dolon. Anyway, more detailed investigation of this settlement is needed in order to reconstruct the possible spatial distribution of exposure rate over Kanonerka at the time of exposure. Contemporary measurements of the ^{137}Cs deposition density over the settlement might be useful for that purpose.

CONCLUSIONS

1. Of total 456 nuclear tests conducted at the Semipalatinsk Test Site during 40 years (1949–1989), only 11 events might have resulted in substantial exposure to the populations of the Republic of Kazakhstan (more than 5 mSv of the effective dose during the first year after the explosion).
2. The available single historical measurement of exposure rate for Dolon was likely performed at the axis of the radioactive trace. So, the dose estimates based on this historical measurement should be considered as possible maximum individual external dose rather than average dose for the residents of this village.
3. The dose estimate for Kanonerka given in this paper based on historical measurement of exposure rate is consistent with that derived from the TL measurements within a factor of two. This difference might be explained by a variation of fallout over this village.
4. Taking into account the paucity of historical measurements of exposure rates and contemporary TL measurements in bricks (that were exposed at that time and are available so far), it looks reasonable to use the suggestion to consider the contemporary measurements of ^{137}Cs in soil over a settlement as a more representative characteristic related to a possible range of doses received by the population.^{4,20,23)}
5. The methodology described in this paper was used for external dose assessment for the cohort members at an initial stage of an ongoing epidemiological study conducted by the U.S. National Cancer Institute in the Republic of Kazakhstan. Recently revised methods and estimates of external dose for that cohort are given in another paper²⁴⁾ in this conference.

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